Beam clean-up and combining via stimulated scattering in liquid crystals

B.Ya. Zeldovich, I.V. Ciapurin L.B. Glebov, C. Tsai, M.C. Stickley,
School of Optics / CREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando FL 32816-2700
Phone (407) 823-6831, FAX (407) 823-6880, boris@creol.ucf.edu

Abstract: Orientational stimulated scattering from o-wave into e-wave in liquid crystal may combine coherent beams or modes of amplifier(s) into diffraction-limited output. In experiment a 1000 micron liquid crystal layer transmitted undistorted o-wave with low attenuation.

OCIS codes: (140.3300) Laser beam shaping, (160.3710) Liquid crystals, (190.5890) Scattering, stimulated

1. Introduction

Modern diode-pumped fiber lasers and solid-state lasers can work in the regime of Power Amplifiers (PA) and thus provide output power in the scale of Kilowatt and more. Crucial problem exists of making a beam of diffraction quality out of resultant radiation. Combining the outputs of several fiber lasers, when each of them is fed by the same signal from Master Oscillator (MO), and each works on a single transverse mode, may be done by multibeam analogs of Mach-Zender interferometer. The phase of each of the beams there is to be controlled electro-optically. However, clean-up of a beam with distorted (albeit coherent) transverse structure, as well as combining several such beams can not be done directly by the interferometric schemes.

We suggest here the device to clean-up and combine transversely and mutually coherent beams of possibly distorted transverse structure into one diffraction-quality beam. The process in question is Stimulated Orientational Scattering from e-wave into o-wave in a cell with Nematic Liquid Crystal (NLC).

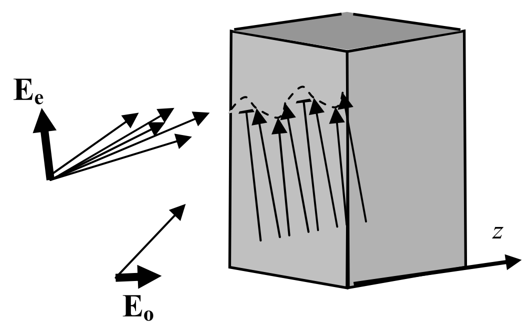

Fig. 1. Interference of distorted pump wave ($\mathbf{E_e}$ in our case) with the diffraction-quality signal beam ($\mathbf{E_o}$ in our case) results in the change of orientation of NLC's director. Scattering of pump into signal by this grating yields energy transfer with the preservation of beam quality.

2. Theoretical estimations

Energy exchange via Stimulated Scattering of light is characterized by gain coefficient

$$g[1/\text{m, intensity}] = G\cdot S_{e,o}\,, \qquad (1)$$

where S is Poynting vector of the wave. Stimulated Scattering by orientation gratings in NLC has this value of gain constant G, see [1, 2]:

$$G = \frac{\pi}{\lambda_{vac}}\left(n_e^2 - n_o^2\right)^2 \frac{1}{K_{22}q^2 c n_e n_o} \equiv \frac{\lambda_{vac}}{\pi}\left(\frac{n_e + n_o}{2}\right)^2 \frac{1}{K_{22} n_o n_e c} \qquad (2)$$

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **10 AUG 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Beam clean-up and combining via stimulated scattering in liquid crystals**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **School of Optics / CREOL, University of Central Florida, 4000 Central Florida Blvd., Orlando FL 32816-2700**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001691, Phase Conjugation for High Energy Lasers., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**22**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Here $S_{e,o} = 0.5cn_{e,o}\varepsilon_0|E_{e,0s}|^2$ are the values of the Poynting vector of the corresponding waves (Watt/m^2), and the coefficient G (m/Watt) gives the intensity gain g of the signal at the optimal frequency shift $\Gamma = +\Omega$, so that $S_o(z)= S_0(0)\exp(gz)$ in the approximation of the undepleted pump, which is e-wave in our case. . The value of G is

$$G = \frac{\pi}{\lambda_{\mathrm{vac}}}\left(n_e^2 - n_o^2\right)^2 \frac{1}{K_{22}q^2 cn_e n_o} \equiv \frac{\lambda_{\mathrm{vac}}}{\pi}\left(\frac{n_e + n_o}{2}\right)^2 \frac{1}{K_{22}n_o n_e c}. \qquad (2)$$

This kind of steady state stimulated scattering in a planar NLC cell has been observed in [3, 4] in complete agreement with theory.

Taking λ_{vac} = 1 μm, elastic constant of NLC $K_{22} = 4\cdot10^{-12}$ Joule/m, refractive index $n\approx1.5$, one gets $G = 6\cdot10^{-4}$ m/Watt ≡ 0.06 cm/Watt. It means that the undepleted amplification factor for the intensity of the signal at the thickness of the cell L = 500 μm and for the pump Poynting vector $S_p = 3\cdot10^3$ Watt/cm^2 is $\exp(GS_pL) = e^9 = 0.8\cdot10^4$. We have all the reasons to assume that such an amplification factor will be quite sufficient for almost complete energy transfer from the multi-transverse-mode pump into the clean signal beam.

The relaxation time $\tau = 1/\Gamma$ depends on the value of the optical anisotropy and on the orientational viscosity of the NLC that is chosen. Taking, for example, $n_e - n_o = 0.2$ and $\eta = 0.1$ Pa·sec, one gets $\Gamma = K_{22}(n_e - n_o)^2 (2\pi/\lambda_{vac})^2/\eta$ = 63 rad/s, $\Omega_{opt}/2\pi = \Gamma/2\pi$ = 10 Hz, $\tau = 1/\Gamma$ = 16 millisecond. That requires that the phase shift between various pump beams or modes should not drift more than 1 radian during 20 millisecond or so. Determining whether this is possible requires physical experiments with the particular laser set-up.

3. Preliminary experimental set-up

We have prepared a cell with Nematic Liquid Crystal of planar orientation. Special configuration of the cell: the thickness changed from 100 micron to 1000 micron at the distance about 48 mm, resulting in a birefringent wedge (mini-prism), which allows to study energy transfer and propagation properties at different values of interaction thickness *L*. Fig. 2 shows propagation of o-wave (left picture) and e-wave (right picture) through 750 microns 0f NLC in the region with rather strong distortions. One sees that o-wave remains practically un-distorted, in agreement with earlier predictions [5] and experiments [6]. Sure, there were regions of the cell with smaller distortions even for e-wave.

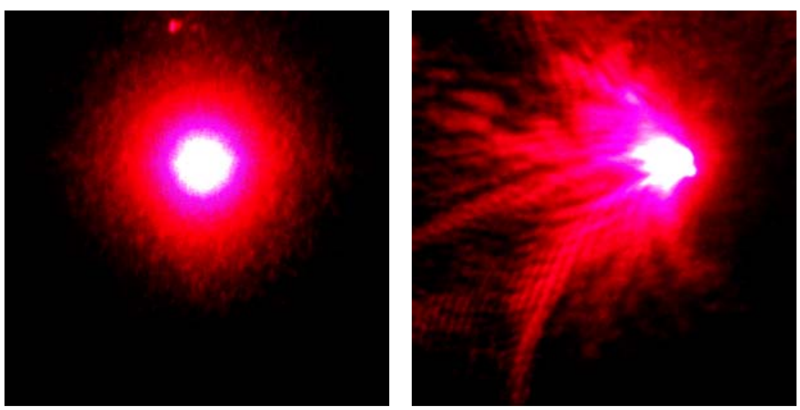

Fig. 2. Un-distorted transmission of ordinary wave (left) and rather strong distortions in the transmission of extraordinary wave (right) through "bad spot" with the thickness 750 microns of planar NLC cell.

We made preliminary measurements of extinction coefficient by this NLC at λ = 632 nm. Since we can not distinguish between actual absorption, extinction due to scattering, and other loss, our estimation is $R_e \leq 9$ [1/cm} and $R_o \leq 8$ [1/cm] respectively. Scattering in LNC scales approximately as $1/\lambda^2$, and therefore we can expect about 4 times smaller scattering at λ = 1.06 micron. In the talk we will present the results of the study of beam clean-up.

To conclude, the possibility of beam clean-up via stimulated scattering in Liquid Crystals seems realistic.

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I. V. Ciapurin, L. B. Glebov, C. Tsai, M. C. Stickley, B. Ya. Zeldovich

School of Optics / CREOL,
University of Central Florida,
Orlando, Florida

CLEO'2003, Baltimore, June 04.

Overview of the talk

1. High-power CW solid-state and fiber lasers are here !
2. Combining several beams and beam clean-up are important problems.
3. Idea: to combine several mutually coherent beams or angular components via Stimulated Scattering.
4. Particular design: Liquid Crystal with o-type signal wave and e-type pump wave.
5. Estimations of the required power and heat transfer.
6. Experimental set-up.
7. Demonstration of Orientational Stimulated Scattering
8. Conclusion.

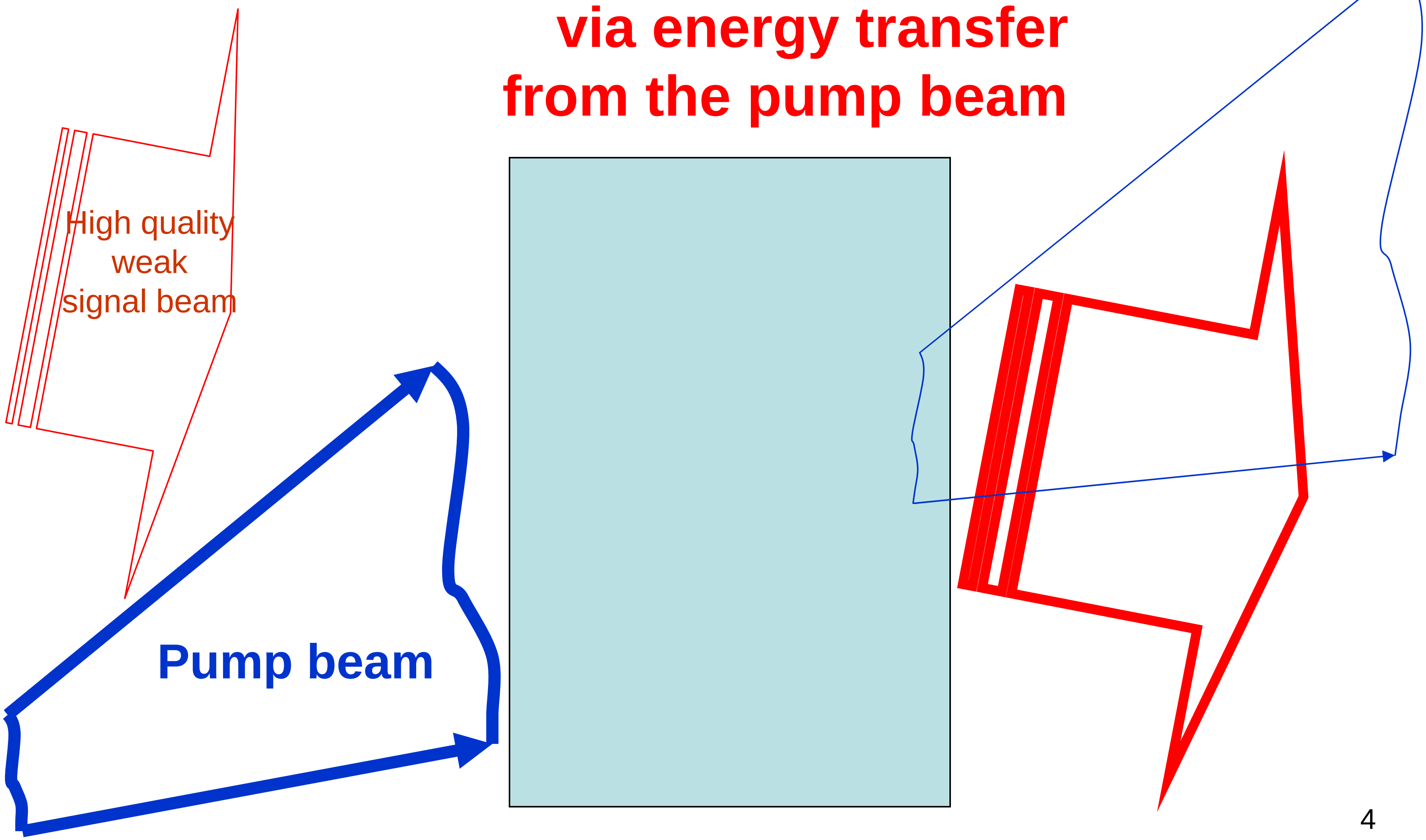
High-power CW solid-state and fiber lasers are here !

They have the power more than 1000 Watt now and promise much more.

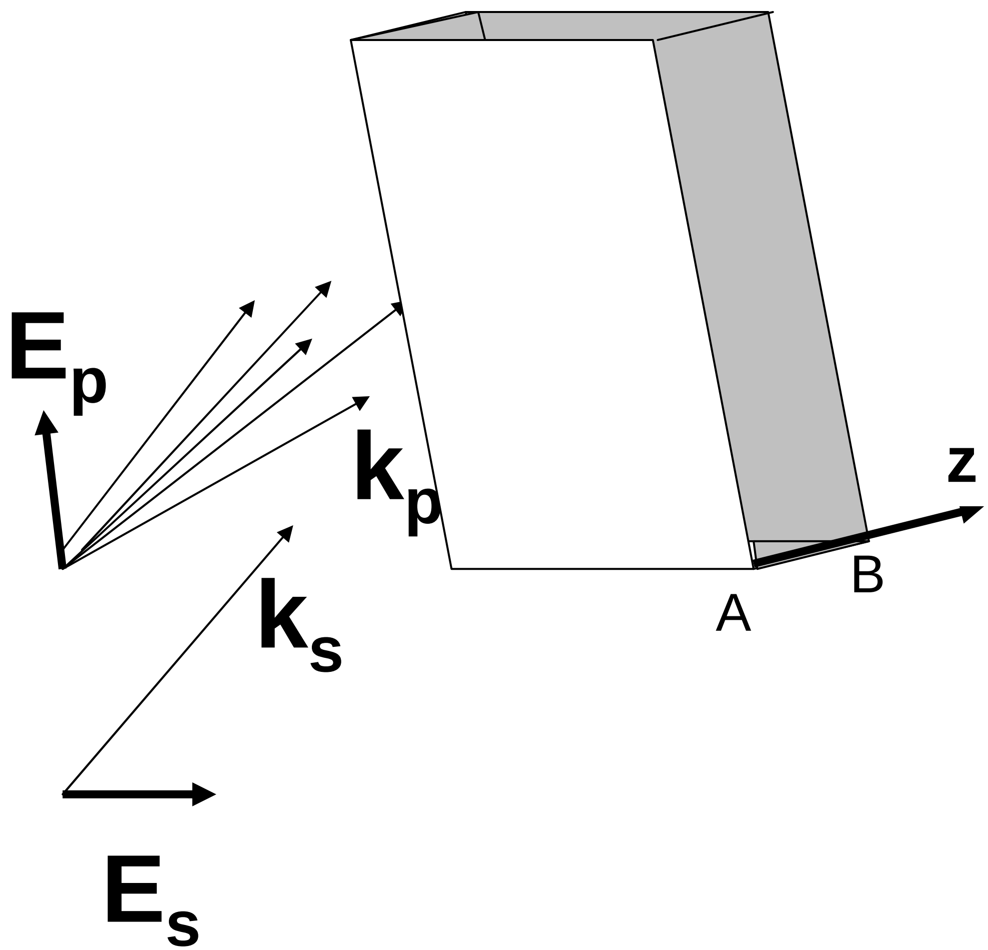
Beam clean-up and combining the energy from several amplifiers look attractive.

However, Louiville's (Lagrange-Helmholtz) theorem does not permit to increase brightness by linear-optical devices.

Stimulated Scattering:
coherent amplification of signal beam via energy transfer from the pump beam

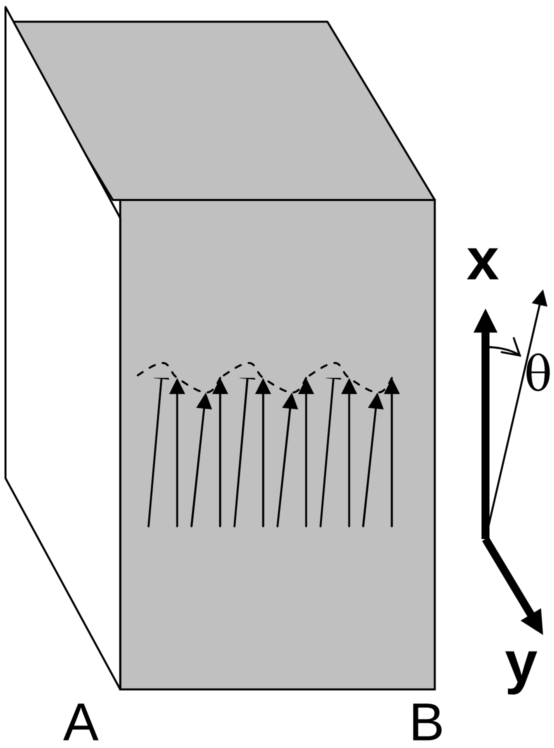


Suggested in this work:
<u>to use orientational Stimulated Scattering in a Nematic Liquid Crystal</u>



Signal plane wave $\mathbf{E_s}$ and inhomogeneous pump wave $\mathbf{E_p}$ have slightly different frequencies, $\omega_p - \omega_s = \Omega$. They illuminate liquid crystal cell with a planar orientation of the director.

Grating-type Orientational Nonlinearity (GRON) in a Nematic Liquid Crystal



Interference of $\mathbf{E_s}$ and $\mathbf{E_p}$ yields the grating with director orientation $\delta\mathbf{d} \propto \exp[i\Omega t - i(\mathbf{k_p} - \mathbf{k_s})\cdot\mathbf{r}]$. Scattering of the pump $\mathbf{E_p}$ by this grating of dielectric permittivity results in amplification of the signal $\mathbf{E_s}$.

References on stimulated scattering in LC:

N. V. Tabirian, A. V. Sukhov, B. Ya. Zeldovich, M.C.L.C. **136**, #1, pp. 1-140, 1986.
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I. C. Khoo et al., Optics Lett., **20**, p. 130, 1995.
N. V. Tabirian, A. V. Sukhov, B. Ya. Zeldovich, JOSA **B, 18**, pp. 1203-06, 2001
(well-saturated regime at pump level about 0.5 Watt for λ = 1.06 μm)

System of basic equations in steady-state approximation

$$\frac{\partial E_{\mathrm{s}}}{\partial z} = E_{\mathrm{s}} \frac{G[(\Omega/\Gamma) - i]}{[1 + (\Omega/\Gamma)^2]} S_{\mathrm{p}}, \qquad \frac{\partial E_{\mathrm{p}}}{\partial z} = -E_{\mathrm{p}} \frac{G[(\Omega/\Gamma) - i]}{[1 + (\Omega/\Gamma)^2]} S_{\mathrm{s}}$$

$$G = \frac{\pi}{\lambda_{\mathrm{vac}}} \left(n_{\mathrm{e}}^2 - n_{\mathrm{o}}^2\right)^2 \frac{1}{K_{22} q^2 c n_{\mathrm{e}} n_{\mathrm{o}}} \equiv \frac{\lambda_{\mathrm{vac}}}{\pi} \left(\frac{n_{\mathrm{e}} + n_{\mathrm{o}}}{2}\right)^2 \frac{1}{K_{22} n_{\mathrm{o}} n_{\mathrm{e}} c}$$

Here E_{p} is pump field, E_{s} is signal field, S_{p}, S_{s} are the corresponding values of Poynting vector, G is the gain constant at the “optimum” frequency shift $\Omega = \Gamma$.

Estimations

For NLC with $n_e - n_o = 0.2$, $\lambda_{vac} = 1\ \mu m$,

$K_{22} = 4 \cdot 10^{-11}$ Newton ($4 \cdot 10^{-6}$ dyne), $n \approx 1.5$,

one gets $G = 6 \cdot 10^{-5}$ m/Watt.

Taking cell thickness L = 0.5 mm,

pump Poynting vector

$S_p = 30$ KWatt/cm$^2 \equiv 3 \cdot 10^8$ Watt/m^2,

one gets signal amplification

$\exp(G S_p L) = e^9 \approx 10^4$.

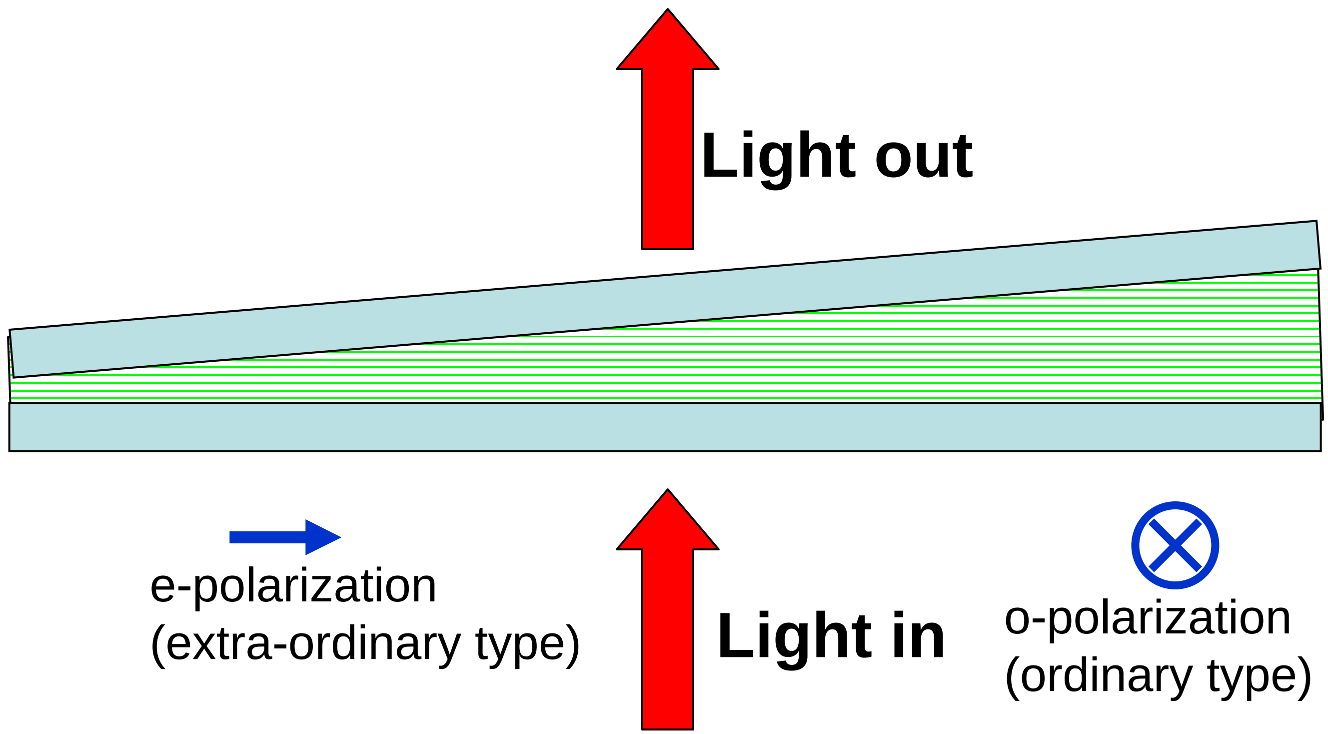
Estimations of thermal load

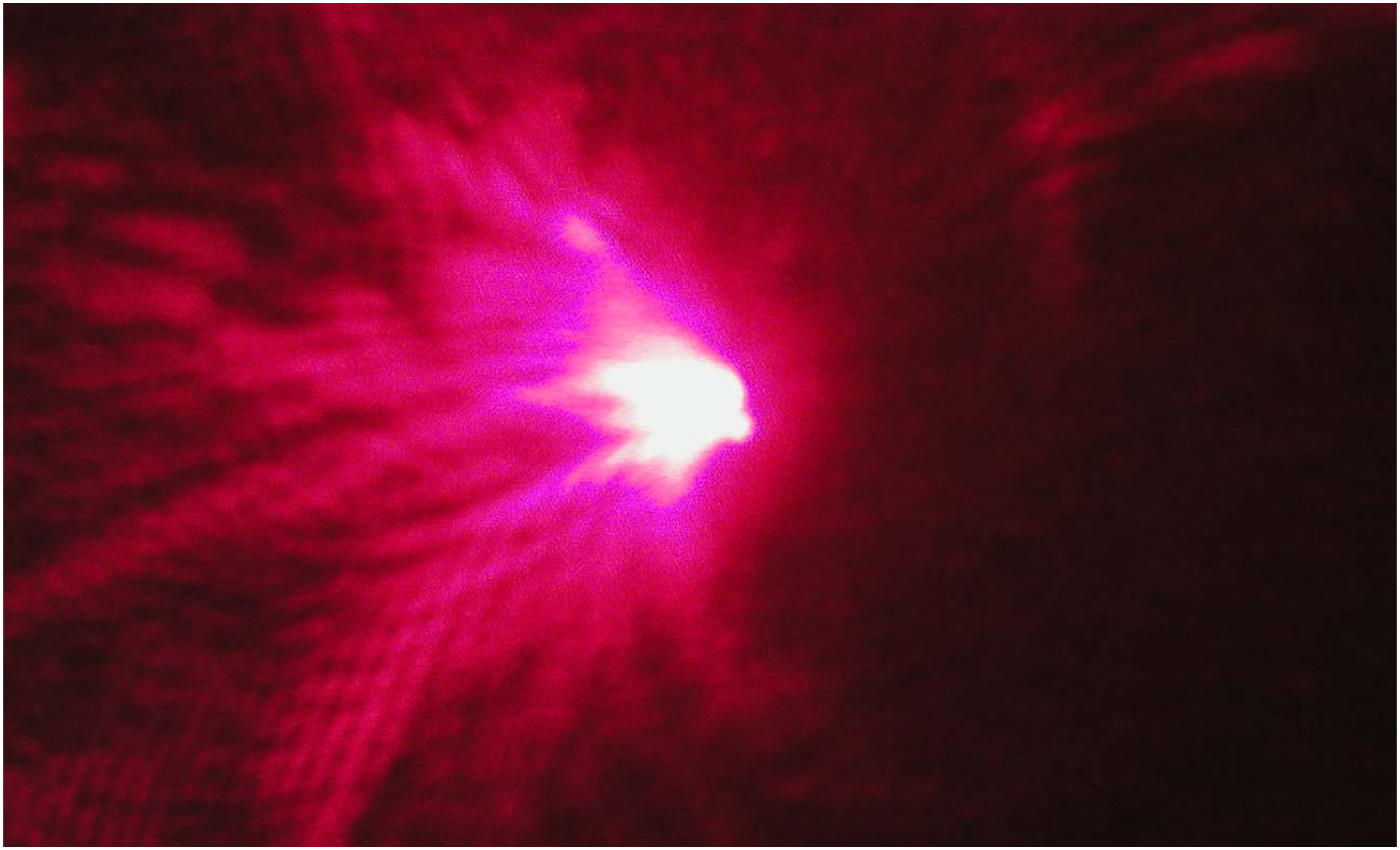
If we take an estimation of the true absorption coefficient, $\alpha \approx$ 0.01 m$^{-1} \equiv$ 0.0001 cm^{-1}, then the fraction of the light absorbed in the *L*=500-micron layer is about $f=\alpha L \approx 5 \cdot 10^{-5}$. At the value of the incident Poynting vector *S* of about 30 KWatt/cm^2, such an absorption yields a thermal power deposition $Sf \approx$ 0.15 Watt/cm^2 of the beam area.

Taking the order of magnitude of thermal conductivity coefficient for NLC $\Lambda \approx 1.3 \cdot 10^{-3}$ Watt/cm·K, and a cell thickness *L* = 500 micron, we get form the steady-state solution of the thermal conductivity equation:
$\delta T_{center} = fSL/8\Lambda \approx 0.7$ K.
The flux of thermal power through one of the two sapphire walls, $0.5fS \approx 0.075$ Watt/cm^2, can be maintained with a temperature gradient of $0.5fS/\Lambda$sapphire = 0.2 K/cm.

Experiment

We used LC cell with Nematic Liquid Crystal of planar orientation.
To try various values of thickness of the cell, we used a wedge-type cell, with the thickness varying from 100 to 1000 micron at 5 cm of length.





Extraordinary wave, λ = 632.8 nm, transmitted trough 800 micron of planar NLC cell. Distortions are rather strong.

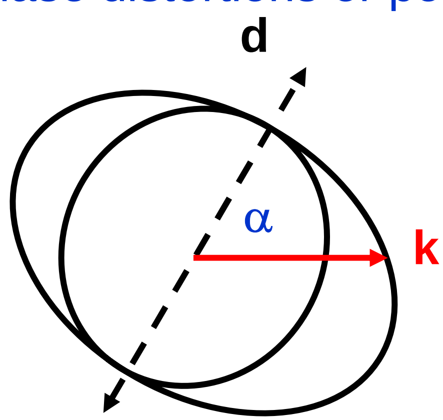
Ordinary wave, λ = 632.8 nm,
transmitted trough 800 micron of planar NLC cell.
Distortions are practically absent.

Reasons for distortion-less transmission of the ordinary-type wave

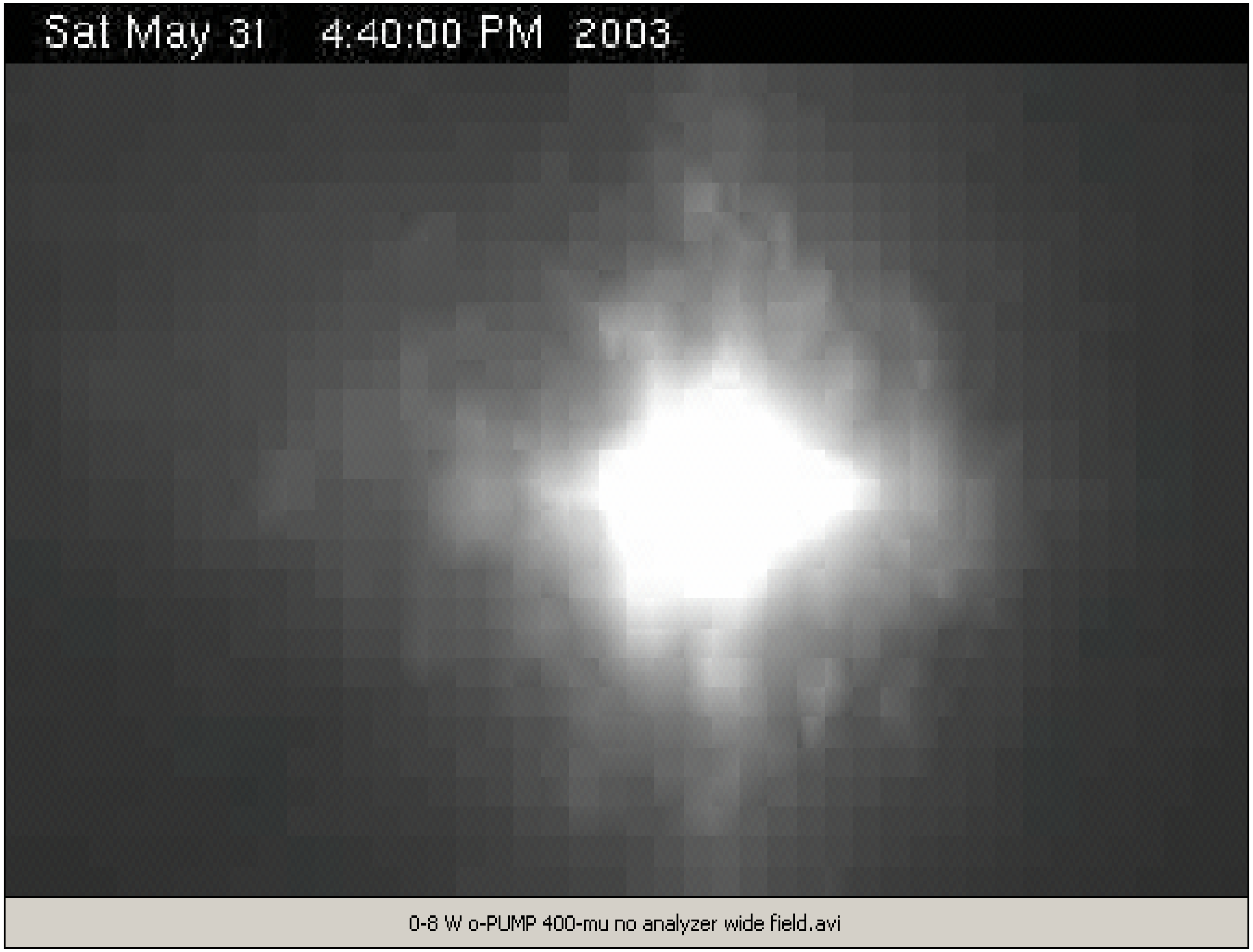
(N. B. Baranova, I. V. Goosev, V. A. Krivoschekov, B. Ya. Zeldovich,
Molecular Crystals & Liquid Crystals J., 210, 155, 1992,
***Distortionless Propagation of O-wave through Inhomogeneous Nematic (Theory and & Experiment.*)**

1. Polarizations of both ordinary and extra-ordinary waves follow adiabatically the local orientation of director.
2. Input and output o- and e-polarizations are prescribed by the boundaries and thus are preserved.
3. Phase velocity of the e-wave varies with the variations of the angle α between propagation **k**-vector and director **d** (ellipsoid !).
4. Phase velocity of the o-wave is constant at any angle α (sphere !).

Therefore o-wave does not acquire
ether phase distortions or polarization distortions.



Observation of Stimulated Grating Orientational Scattering in NLC



λ = 1.08 mkm, Yb-doped IPG fiber laser, output power 100 W, power to the cell 0.8 W. Lens F = 20 cm, beam $\varnothing$ = 5 mm ($FWe^{-2}M$) at the lens.

Observation of Stimulated Grating Orientational Scattering in NLC

λ= 1.08 mkm,
Yb-doped IPG fiber laser, output power 100 W,
power to the cell 3.2 W.
Lens F = 20 cm,
beam ∅ = 5 mm
(FWe^{-2}M)
at the lens.
Cell was out of focus.

Observation of Stimulated Grating Orientational Scattering in NLC

Power to the cell 1.6 W.
Lens F = 20 cm, beam ∅ = 5 mm ($FWe^{-2}M$) at the lens.
Cell was in focus.
Analyzer transmitted mostly the scattered wave. Almost no o-wave pump is left.

Potential problems to be overcome. 1.

$$\frac{\partial E_\mathrm{s}}{\partial z} = E_\mathrm{s} \frac{G\left[\left(\Omega/\Gamma\right) - i\right]}{[1+(\Omega/\Gamma)^2]} S_\mathrm{p}$$

Term (–*i*) means Cross-Phase Modulation (CPM) at the "optimum" frequency shift $\Omega = \Gamma$.
It may distort the phase of the cleaned signal beam.

Some of the ways to overcome CPM's influence.

Make the profile of pump's Poynting vector approximately parabolic.

Take "super-optimum" frequency shift, e.g. $\Omega = 3\Gamma$. Then gain will be damped by factor 0.6, while CPM will be damped by factor 0.1.

Use double-phase conjugation scheme.

Potential problems to be overcome. 2.

Time coherence is required between the signal and the beam(s) to be combined and/or cleaned-up.

What to do about it ?

Coherence is not an issue, if the spectrum of our MO-PA device is narrow enough.

Equal optical paths for various channels, angular components etc. should be provided within the coherence length.

Conclusions

1. Stimulated Scattering in Nematic LC is suggested for the beam combining and clean-up.
2. Inhomogeneities of NLC orientation do not distort ordinary wave, even at L = 1 mm.
3. Stimulated scattering at 1.06 μm is demonstrated in the work by Tabirian, Sukhov & Zeldovich, and at 1.08 μm here.
4. NLC cell and LC material within it are shown to tolerate at least 100 KWatt / cm^2 of CW light.
5. Perspectives of beam combining and clean-up for high-average power beams look promising.